Universitatea Tehnică
de Construcții București

DOCTORAL THESIS

SUMMARY

CONTRIBUTIONS TO THE PRODUCTION, APPLICATION AND BEHAVIOUR OF FIBRE-REINFORCED CONCRETE UNDER DIFFERENT TYPES OF LOADING

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CHAPTER 1. INTRODUCTION

Concrete is the most widely used construction material worldwide; however, one of its fundamental limitations is its low capacity to resist tensile stresses. Consequently, cracking behaviour is essential from the standpoint of both structural resistance and durability. One solution developed to improve the tensile response and limit crack propagation is the introduction of fibres dispersed throughout the concrete matrix, thus producing fibre-reinforced concrete (FRC). The thesis systematically analyses this composite material, with particular emphasis on steel fibres and on their potential use in structural members, including prestressed concrete members.

The working principle of fibre-reinforced concrete is based on the transfer of stresses by fibres crossing cracks that develop in the concrete matrix. After matrix cracking, the fibres continue to bridge the crack faces and enable residual tensile stresses to be carried. This mechanism increases ductility, improves post-cracking behaviour and enhances energy absorption capacity. Compared with plain concrete, fibre-reinforced concrete exhibits significant residual strength and a superior capacity to control cracking.

The thesis points out that the use of fibres in construction materials is not a new concept. Early forms of dispersed reinforcement were used in antiquity by incorporating plant fibres into clay-based mixtures. Natural fibres, such as horsehair, were subsequently used, while modern technological development led to steel, glass and polymer fibres. For steel fibre-reinforced concrete, the first patents date from the second half of the nineteenth century and were followed by extensive research into the influence of fibre shape and geometry on bond and structural performance.

Based on the literature, steel fibres should not be regarded solely as a means of increasing mechanical strength. Their main role is to control cracking and improve energy absorption, impact resistance, behaviour under repeated loading and long-term durability. These characteristics have extended the use of fibre-reinforced concrete to complex structural applications, including prestressed members and structures subjected to severe loading conditions.

The main objective of the thesis is the experimental evaluation of the shear behaviour of prestressed concrete members incorporating two transverse reinforcement solutions: conventional stirrups and dispersed steel-fibre reinforcement. The research investigates the extent to which fibres can reduce or partially replace conventional transverse reinforcement without compromising structural safety. Load-bearing capacity, stiffness, failure mechanisms, crack development and post-cracking behaviour are therefore analysed.

To achieve this goal, several specific objectives were formulated. These include the analysis of the application areas of FRC, the comparison of different types of fibers, the evaluation of technological aspects and mechanical properties, the presentation of existing design rules, the study of durability and the performance of parametric studies on the influence of fibers on structural behavior. The central element of the research is the experimental program carried out on prestressed concrete purlins, through which the solutions with stirrups and those based on dispersed reinforcement are directly compared.

The originality of the work results from the integrated approach to the issue of FRC. The thesis is not limited to presenting the current state of knowledge, but includes parametric studies, design analyses and an extensive experimental program oriented towards prestressed elements. This aims to formulate conclusions and recommendations applicable in design and execution practice.

CHAPTER 2. APPLICATIONS OF FIBRE-REINFORCED CONCRETE

The second chapter presents the main fields of application of fibre-reinforced concrete and highlights its advantages over traditional solutions. The analysis ranges from slabs and foundations to special structures, precast elements and earthquake-resistant structures. Developments in production technology and design methods have continuously broadened the use of FRC, particularly where crack control and reduction of conventional reinforcement are important objectives.

An important area of application is ground-supported slabs and pile-supported slabs. In these elements, the use of fibers allows for a reduction in the amount of conventional reinforcement and simplifies execution. The fibers help control cracks generated by shrinkage and service loads and ensure a more uniform distribution of stresses in the concrete mass. Also, by limiting the opening of cracks, a more favorable behavior is obtained in terms of durability and maintenance costs.

Ground-supported slabs and pile-supported slabs are major applications. Fibres can reduce conventional reinforcement and simplify construction, while controlling cracks caused by shrinkage and service loads and promoting a more uniform stress distribution. Limiting crack widths also improves durability and may reduce maintenance costs. Pile-supported slabs are among the most widespread FRC applications in modern industrial and logistics facilities in Europe, where loads of about 50 kN/m² or more may occur. Solutions range from fibre-only reinforcement to hybrid systems combining fibres with local conventional reinforcement over piles.

Foundation rafts and wind-turbine foundations are also of particular interest. Their large concrete volumes and significant static and dynamic actions make crack control important. Fibres help reduce shrinkage- and temperature-induced cracking and can improve service behaviour. In wind-turbine foundations, where cyclic actions are important, dispersed reinforcement may contribute significantly to durability and lower maintenance requirements.

A particularly interesting area is the foundation slabs and foundations for wind turbines. These structures are characterized by large volumes of concrete and by significant stresses generated by static and dynamic loads. The introduction of fibers contributes to the reduction of shrinkage cracking and thermal variations, as well as to the improvement of the service behavior. In the case of foundations for wind turbines, where cyclic stresses are very important, dispersed reinforcement can significantly contribute to increasing durability and reducing maintenance costs.

The chapter continues with the use of FRC in supporting structures and shell structures. In the case of retaining walls, the use of fibers leads to improved cracking resistance and a reduction in the amount of conventional reinforcement required. For shell structures, characterized by reduced thicknesses and complex geometries, fibers allow a three-dimensional distribution of the reinforcement and contribute to the control of local stresses. These advantages are particularly important in the case of structures with curved shapes or large prefabricated elements.

Bridge decks are another area where dispersed reinforcement has proven its effectiveness. Fibers help limit cracking caused by repeated loads and thermal variations and improve fatigue behavior. By reducing the opening of cracks, the risk of aggressive agents penetrating is reduced and the durability of the structure is improved. In addition, the use of fibers can lead to reduced execution costs and simplified reinforcement processes.

Of particular interest for the thesis topic is the use of FRC in prestressed prefabricated elements and in general in prestressed elements. It is emphasized that numerous recent researches have demonstrated the potential of steel fibers to contribute to the taking over of shear forces and to the control of cracking in such elements. This observation constitutes one of the main motivations of the experimental program subsequently developed within the thesis. The use of fibers can lead to a reduction in the amount of stirrups and to a simplification of the prefabrication process, without diminishing the level of structural safety.

The last category analyzed is represented by earthquake-resistant structures. In their case, FRC contributes to increasing the energy dissipation capacity and improving post-cracking behavior. The fibers limit the rapid propagation of cracks and allow the development of more ductile failure mechanisms. For this reason, dispersed reinforcement is considered a promising solution for improving the seismic performance of some categories of reinforced concrete structures.

In conclusion, the analysis of the application areas demonstrates that FRC is not only an alternative to conventional reinforcement, but a material capable of providing effective solutions to numerous technological and structural problems. The main advantages identified are cracking control, increased ductility, improved durability and the possibility of reducing classical reinforcement in certain situations. These arguments justify the growing interest in the use of fibers in structural elements and constitute the foundation of the research developed in the following chapters.

CHAPTER 3. TYPES OF FIBERS

The third chapter is dedicated to the presentation and classification of the fibers used in the production of FRC. The mechanical behavior of this material is directly influenced by the properties of the fibers used, their geometry, the way they are distributed in the concrete mass and the characteristics of the fiber-matrix interaction. For this reason, the choice of the type of fibers is one of the most important steps in the design of a FRC intended for structural applications.

It is highlighted that the performance of fibers is influenced by a series of fundamental geometric characteristics, the most important of which are length, equivalent diameter and aspect ratio. The length of the fibers influences their ability to cross cracks and transfer stresses after cracking occurs. Fibers that are too short cannot develop sufficient anchorage in the matrix, while very long fibers can generate technological difficulties and agglomeration phenomena. The choice of the optimal length must be made depending on the dimensions of the aggregates and the structural application pursued.

The equivalent diameter is another essential parameter because it influences the contact surface between the fiber and the matrix and implicitly the level of adhesion efforts that can be developed. Reducing the diameter leads to an increase in the specific surface area and to an improvement in the efficiency of the dispersed reinforcement, but it can affect the technological process and production costs. In practice, the aim is to achieve a balance between mechanical performance and technological requirements.

A frequently used indicator for fiber characterization is the aspect ratio, defined as the ratio between the fiber length and its equivalent diameter. This parameter directly influences the ability of the fibers to absorb stresses after concrete cracking. In general, fibers with a high aspect ratio provide a greater stress transfer capacity and a more favorable post-cracking behavior. However, an excessive increase in this ratio can lead to mixing difficulties and the appearance of agglomerations, which affects the uniformity of fiber distribution in the concrete mass.

Based on the geometric shape, fibers used in concrete can be classified into straight fibers, wavy fibers, fibers with anchored ends, twisted fibers and fibers with various special configurations developed to improve adhesion. The evolution of production technologies has constantly aimed at increasing the efficiency of the anchoring mechanism in concrete and developing shapes capable of ensuring increased pullout resistance. The shape of the fiber influences both the cracking behavior and the level of residual strengths developed after the appearance of cracks.

The thesis analyzes the main categories of fibers used in construction. Steel fibers represent the most important category for structural applications. They are usually made of high-strength steel and are available in a wide range of shapes and sizes. The main advantages of steel fibers are their high modulus of elasticity, high tensile strength and the ability to contribute significantly to the absorption of post-cracking stresses. Due to these characteristics, steel fibers are considered the most effective for applications where the reduction of conventional reinforcement or the improvement of structural behavior is sought.

Polymer fibers are mainly used to control shrinkage cracking and to improve the behavior in the early stages of the hardening process. Compared to metallic fibers, they have a lower modulus of elasticity and contribute to a lesser extent to the absorption of structural stresses. However, the advantages related to corrosion resistance and ease of use recommend them for many specific applications. Similarly, glass fibers and other special fibers are used in situations where particular properties are required, such as corrosion resistance or weight reduction.

An important aspect analyzed is the mechanism of interaction between the fiber and the matrix. The performance of a fiber does not depend exclusively on the properties of the material from which it is made, but also on its ability to develop adhesion and anchoring efforts in concrete. In the case of modern metal fibers, anchoring is improved by the use of deformed ends or special geometries that increase the pullout resistance and allow the development of higher efforts after cracking of the concrete. This mechanism is the basis of the post-cracking behavior of FRC.

The chapter also deals with aspects related to packaging, identification and certification. In the context of the use of fibers in structural applications, it is essential that they comply with European requirements regarding conformity and traceability. The requirements regarding CE marking and declarations of performance that must accompany products used in construction are presented. These requirements allow designers and contractors to use products with verified characteristics and ensure compliance of the works with the regulations in force.

In conclusion, the analysis of fiber types highlights the fact that the choice of fibers must be made according to the requirements of the application and the desired performance. For structural applications and for the prestressed elements analyzed in the thesis, metal fibers with high anchoring performance represent the optimal solution due to their ability to contribute to the absorption of shear forces and to the improvement of post-cracking behavior.

CHAPTER 4. TECHNOLOGICAL ASPECTS

The fourth chapter is dedicated to the technological aspects associated with the production and use of FRC. Although the introduction of fibers leads to the improvement of important mechanical properties, it also generates a series of technological peculiarities that must be taken into account from the design phase of the concrete composition. The final behavior of the material depends largely on the way in which the fibers are distributed in the matrix and on the quality of the technological process of production and placing.

The first part of the chapter analyzes the principles of composition of FRC. The introduction of fibers influences the internal structure of the mixture and modifies the relationships between the classic components of concrete. For this reason, the composition must be adapted so as to ensure both the uniform dispersion of the fibers and the workability necessary for transport, casting and compaction. It is highlighted that obtaining a high-performance concrete involves finding a balance between technological and structural requirements.

One of the most important consequences of introducing fibers is the reduction of the workability of the mixture. The fibers create a three-dimensional network that hinders the movement of particles and increases the internal resistance to flow. The higher the fiber dosage and the higher the geometric ratio, the more pronounced the effect on workability becomes. For this reason, the use of superplasticizing additives and optimization of the granulometric composition are frequently necessary measures to maintain the workability characteristics.

In addition to the influence on workability, fibers also affect the stability and homogeneity of the concrete mix. An uneven distribution of fibers can lead to the appearance of areas with high concentrations and poorly reinforced areas, which determines significant variations in mechanical properties. For this reason, the mixing process must be designed to ensure uniform dispersion of fibers throughout the mass of the concrete. It is emphasized that homogeneity is one of the essential conditions for obtaining reproducible results and for the efficient use of dispersed reinforcement.

A phenomenon specific to FRC is fiber agglomeration. It occurs when the fibers are not uniformly distributed and form local conglomerates that affect both the workability and mechanical performance of the concrete. Agglomeration can be favored by high fiber dosages, long fiber lengths, or improper mixing procedures. To avoid this phenomenon, it is necessary to comply with an appropriate fiber introduction technology and rigorous control of the preparation process.

The chapter also analyzes the influence of fibers on the air content of concrete. The introduction of fibers can modify the pore structure and can influence the amount of air entrained in the mixture. This aspect is important because it affects both the mechanical properties and the durability of the material. In practice, these effects must be taken into account when establishing the composition and evaluating the characteristics of fresh concrete.

Particular attention is paid to the orientation of the fibers. Although in most cases it is considered that the fibers are randomly distributed, numerous studies have demonstrated that the casting and compaction processes can generate preferential orientations. This orientation significantly influences the mechanical properties of the element and can lead to important differences between the theoretical and the real behavior. In the case of structural elements predominantly stressed in a certain direction, the orientation of the fibers can have favorable or unfavorable effects on the strength and ductility.

The process of putting into operation is another essential aspect analyzed in the chapter. The methods of casting, compacting, finishing and treating FRC are presented, highlighting the need to adapt the technology to the specific characteristics of the mixture. Fibers can influence the response of the concrete to vibration and can modify the appearance of the finished surfaces, which is why the execution processes must be carefully controlled. In the case of prefabricated elements, these aspects are particularly important because they influence both the quality of the finished product and the efficiency of the industrial process.

The main stages of the production of FRC are summarized, starting from the choice of component materials and continuing with the establishment of the composition, preparation of the mixture, transportation, pouring, compaction and curing of the concrete. Each stage has a direct influence on the final performance of the material, and neglecting one of them can lead to a decrease in the advantages offered by dispersed reinforcement.

In conclusion, the chapter demonstrates that the performance of FRC.

CHAPTER 5. FUNDAMENTAL CHARACTERISTICS OF FIBRE-REINFORCED CONCRETE

Chapter five analyzes the fundamental properties that differentiate FRC from conventional concrete. The focus is on the tensile behavior, adhesion mechanisms, flexural response, and the interaction between dispersed and conventional reinforcement. These aspects represent the theoretical basis for understanding how fibers influence the structural behavior of concrete elements.

The first section is dedicated to tensile behavior and the fiber–matrix interaction mechanism. In conventional concrete, after reaching tensile strength, cracks develop rapidly and lead to an almost complete loss of stress-bearing capacity. In contrast, in FRC, fibers cross the cracks and continue to transfer stresses between their two faces. This phenomenon, known as “bridging,” is the fundamental mechanism by which fibers contribute to improving structural behavior.

The fiber–matrix interaction depends on the fiber characteristics, the concrete properties and the quality of the contact area between the two materials. When the crack starts to open, the stresses are transferred by adhesion and mechanical anchoring mechanisms. As the crack opening increases, the fibers develop tensile strength and allow the absorption of significant residual stresses. The level of these stresses largely determines the strength and ductility class of the FRC.

An essential characteristic highlighted in the thesis is the effective post-cracking tensile strength. This represents the ability of FRC to continue to absorb stresses after the appearance of cracks and constitutes the main advantage over conventional concrete. The residual strength is influenced by the type of fibers, dosage, their orientation and matrix properties. In practice, this characteristic is used to classify FRC and to integrate the contribution of fibers in design calculations.

The second part of the chapter is dedicated to the adhesion phenomenon. The bond forces between concrete and reinforcement, the anchoring mechanisms and the conditions of overlap bonding are analyzed. It is highlighted that the presence of fibers can favorably influence the bond behavior by limiting the development of cracks and reducing local stress concentrations. In certain situations, this effect can lead to an improvement in the overall behavior of conventionally reinforced elements.

The analysis of the bending behavior and the influence of fibers on the response of structural elements follows. Experimental results presented in the specialized literature show that fibers contribute to increasing the rigidity after cracking, reducing the crack opening and developing a more ductile behavior.

One aspect analyzed in the chapter is the depth effect ("size effect"), a well-known phenomenon in concrete mechanics. Numerous researches have demonstrated that the shear strength and cracking behavior of concrete elements are influenced by their dimensions. As the height of the element increases, the nominal shear strength tends to decrease. It is highlighted that the presence of fibers can partially reduce the influence of this phenomenon by limiting the propagation of cracks and by redistributing the stresses in the extended area. However, the effect is not completely eliminated, and the design must take into account the real dimensions of the structural elements.

The chapter further deals with the interaction between dispersed reinforcement and conventional reinforcement. One of the important conclusions of the specialized literature is that fibers and classical reinforcements should not be seen as competing solutions, but as complementary elements. Conventional reinforcements ensure the transfer of the main stresses and the control of the overall behavior of the structure, while fibers contribute to the control of cracking, to the improvement of ductility and to the increase of residual strengths. In many applications, the simultaneous use of the two systems leads to superior performances compared to the separate use of each.

Particular attention is paid to the behavior under shear force, since this represents one of the central themes of the thesis. After the appearance of inclined cracks, the fibers that intersect these cracks contribute to the transfer of stresses and limit their development. This mechanism can lead to an increase in the load-bearing capacity and to a modification of the failure mode. Numerous cited studies show that metal fibers can significantly contribute to the resistance to shear force, but their efficiency depends on the type of fibers, the dosage and the structural configuration analyzed.

In the case of prestressed elements, the interaction between prestressing and dispersed reinforcement is particularly interesting. Prestressing limits crack development and reduces tensile stresses, while fibers contribute to controlling cracks that appear in advanced loading phases. This combination can lead to significant improvement of shear behavior and increased structural safety. This hypothesis is experimentally verified in the applied part of the thesis.

In conclusion, the chapter demonstrates that FRC is a material with fundamentally different properties compared to conventional concrete. The ability to absorb stresses after cracking, crack propagation control and ductility improvement are the main advantages that justify the use of fibers in structural applications. These characteristics are the basis of the design models and the experimental program presented in the following chapters.

CHAPTER 6. EXPERIMENTAL DETERMINATION OF THE MECHANICAL PROPERTIES OF FRC

The sixth chapter is devoted to the experimental methods used to characterize the mechanical properties of FRC. Since the behavior of this material differs significantly from that of conventional concrete, classical methods based exclusively on the determination of compressive strength are insufficient for the complete description of its structural response. For this reason, specific procedures have been developed to evaluate the post-cracking behavior and the contribution of fibers to the effort absorption.

The first category of tests analyzed is represented by compression tests. Although fibers influence the compressive strength to a relatively small extent, they can modify the behavior after reaching the maximum load. In many cases, the presence of fibers leads to increased ductility and reduced brittleness of failure. However, it is emphasized that the main benefit of fibers does not consist in increasing the compressive strength, but in improving the behavior under tension and cracking.

Tensile and bending tests are of much greater importance. In practice, direct tensile testing is difficult; consequently, FRC is commonly characterised through flexural tests on notched prismatic beams. These tests determine residual strengths at specified crack-mouth opening displacements (CMOD) and provide essential information on post-cracking behaviour.

European standardised procedures use these parameters for material classification and for incorporating fibre contribution into design. Residual strengths are therefore fundamental quantities. Toughness and energy absorption capacity are also important, particularly for members subjected to dynamic loading, impact or seismic actions. Fibre distribution and orientation introduce additional natural scatter into experimental results, making adequate specimen numbers, technological control and well-designed experimental programmes essential.

The chapter also deals with the methods of evaluating the toughness and energy absorption capacity. These properties are particularly important for elements subjected to dynamic loads, impact or seismic actions. The fibers contribute to a significant increase in the energy absorbed before failure, which leads to the development of a more ductile and safer behavior. For this reason, the evaluation of toughness is an essential element in the characterization of FRC.

Another issue addressed is the natural dispersion of the experimental results. Unlike conventional concrete, in the case of FRC there is an additional influence generated by the random distribution and orientation of the fibers. For this reason, experimental results show a greater variability and require an adequate number of samples to obtain relevant statistical conclusions. The importance of technological control and the use of well-designed experimental programs to reduce uncertainties is emphasized.

In conclusion, the chapter highlights the fact that the mechanical properties of FRC must be evaluated by methods capable of capturing the post-cracking behavior and the effective contribution of fibers. Residual strengths, toughness and energy absorption capacity are essential parameters for the characterization of this material and for its use in structural applications.

CHAPTER 7. DESIGN CONSIDERATIONS FOR FRC MEMBERS

The seventh chapter analyzes how the contribution of fibers can be integrated into the design calculations and presents the main recommendations and models developed at international level for the dimensioning of FRC elements.

The seventh chapter is dedicated to design aspects and follows how the contribution of fibers can be quantified and introduced into the calculation of structural elements. The need for specific design rules results from the fact that FRC exhibits a different behavior compared to conventional concrete, especially after the appearance of cracks. Consequently, classic models based exclusively on compressive strength and conventional reinforcement must be adapted to take into account the contribution of residual strengths provided by fibers.

The main international documents and recommendations used for the design of structures made of FRC are presented. In particular, the recommendations of the fib Model Code and the rules of EN 1992-1-1 and various European guides that allow the integration of the contribution of fibers in the checks at the ultimate and serviceability limit states are analyzed. These documents use experimentally determined residual strengths as basic parameters and allow the evaluation of the effect of fibers on structural behavior.

The first problem addressed is the design for bending. In the case of dispersed reinforced elements, the fibers contribute to the take-up of tensile stresses after cracking and can participate in the resistance of the section. Depending on the level of residual strengths and the percentage of conventional reinforcement, the contribution of the fibers can lead to an increase in the moment capacity and to an improvement in the ductility of the element. However, it is emphasized that dispersed reinforcement does not eliminate the need for main strength reinforcement, but acts complementary to them.

Special attention is paid to the shear force checks, since they are directly related to the central theme of the thesis. Modern calculation models admit that fibers intersecting inclined cracks contribute to the transfer of stresses and to an increase in the bearing capacity. Consequently, the contribution of dispersed reinforcement can be explicitly taken into account in the calculation of the shear force resistance. The level of this contribution depends on the properties of the fibers, the dosage used and the characteristics of the concrete.

The chapter also analyzes the checks at the serviceability limit states. Fibers favorably influence the cracking behavior by reducing the crack opening and by distributing them more uniformly. This effect can lead to improved durability and to a reduction in problems associated with the penetration of aggressive agents into the concrete. In certain situations, the contribution of fibers can allow the reduction of reinforcement used exclusively for cracking control.

Different calculation models are also presented for the evaluation of the shear strength of fiber-reinforced elements. These models start from the classical stress transfer mechanisms and introduce additional terms that describe the contribution of fibers to crack crossing. The advantages and limitations of each approach are highlighted and the conditions under which they can be used in design practice are discussed.

An important conclusion of the chapter is that fibers should not be considered a universal replacement for conventional reinforcement. On the contrary, they can reduce the need for transverse reinforcement under certain conditions and can significantly improve the structural behavior. The extent to which this reduction is possible needs to be established through experimental research and appropriate validations. This conclusion constitutes the starting point for the parametric studies and experimental program presented in the following chapters.

CHAPTER 8. DURABILITY OF FIBRE-REINFORCED CONCRETE

The eighth chapter deals with one of the most important aspects associated with the use of concrete in construction, namely durability. The structural performance of an element is not determined exclusively by its initial load-bearing capacity, but also by the possibility of maintaining its properties throughout its service life. In this context, the influence of fibers on the main degradation mechanisms affecting concrete and reinforcement is analyzed.

The first issue addressed is related to the influence of fibers on cracking and permeability of concrete. In general, fibers contribute to limiting the opening of cracks and to their more uniform distribution. This effect leads to a reduction in permeability and an improvement in behavior in aggressive environments. Since the penetration of water, chlorine ions and other aggressive agents is closely related to the development of cracks, their control is one of the main benefits of dispersed reinforcement.

The chapter continues with the phenomenon of corrosion. In the case of metal fibers, there are often concerns regarding the possibility of corrosion and its effects on structural behavior. Based on the results presented in the specialized literature, it is shown that the fibers inside the concrete mass benefit from the protection offered by the alkaline environment and that any superficial corrosion phenomena generally have a reduced influence on the structural performances. However, the situation must be analyzed differently depending on the exposure conditions and the type of fibers used.

Another important mechanism analyzed is the behavior during freeze-thaw cycles. The repeated action of thermal cycles can produce progressive degradation of the pore structure and of the contact area between the concrete components. The fibers can contribute to limiting the development of cracks and maintaining structural integrity, but the overall performance depends primarily on the quality of the concrete and the measures adopted to ensure resistance to freeze-thaw.

Fatigue behavior is also discussed. In the case of structures subjected to repeated loads, such as bridges, industrial elements or offshore structures, fibers contribute to reducing the speed of crack propagation and increasing the service life. The energy absorption capacity and the stress transfer mechanism through the fibers allow the development of a more favorable behavior under cyclic loading conditions.

A separate section is devoted to the behavior under impact and dynamic loads. Due to the high energy absorption capacity, FRC can present superior performances compared to conventional concrete in the case of accidental actions. This aspect explains its use in special structures, protective elements and constructions subjected to severe operating conditions.

In conclusion, the chapter demonstrates that dispersed reinforcement can significantly contribute to improving durability by controlling cracking and limiting the development of degradation mechanisms. However, the final performance still depends on the quality of the concrete, the operating conditions and compliance with the general design and execution requirements.

CHAPTER 9. DESIGN EXAMPLES AND PARAMETRIC STUDIES

The ninth chapter represents the transition from theoretical analysis to practical applications and aims to evaluate the influence of dispersed reinforcement on structural behavior through calculation examples and parametric studies. The main objective is to identify how the modification of the specific parameters of FRC influences the strength and behavior of structural elements.

The first part presents examples of dimensioning and verification using the calculation relationships discussed in the previous chapter. It aims to highlight how the experimentally determined residual strengths can be introduced into the design calculations and influence the final results. Both the ultimate limit state and the serviceability limit state verifications are analyzed.

The parametric studies follow the influence of the main factors that characterize FRC: fiber dosage, fiber mechanical characteristics, concrete strength and structural element dimensions. The results show that increasing the fiber dosage generally leads to increased residual strengths and improved shear and cracking behavior. However, the additional efficiency obtained by increasing the dosage is not unlimited and must be analyzed in relation to the technological and economic implications.

CHAPTER 10. EXPERIMENTAL RESEARCH

10.1 Introduction

The experimental tests aimed to demonstrate the possibility of partially replacing, in the central area, the transverse stirrup reinforcement with dispersed steel-fibre reinforcement in the case of prestressed concrete purlins. Several possible implications of this replacement were investigated, mainly related to:

- Bearing capacity, including shear force;
- Evolution of the deformation state in the central area;
- Evolution of deflection;

10.2 Experimental tests for determining the FRC class

The concrete was of compressive strength class C 50/60.

The dosage of steel fibers type Dramix 5D 65/60BG was 30 kg/m³.

The failure mode of the specimens after the test is illustrated in Fig. 1. This figure shows an irregular crack propagation, which although has a direction induced by the type and configuration of the load, also follows the defects of the material. For this reason, there is also a significant variability in the results, both in terms of the failure mode and the experimental curves. In the bottom view, the presence of fibers crossing the crack is also observed, generating the bridging effect, ensuring resistance in the cracked area. As can be seen, their arrangement is random. Some of them break before failure, or are torn off, but it is observed that some of them remain anchored on both sides of the crack.

a) b)

Fig. 1. The failure mode of the specimen. Side view (a) and bottom view (b).

The experimental force/CMOD curves are shown in Fig. 2.

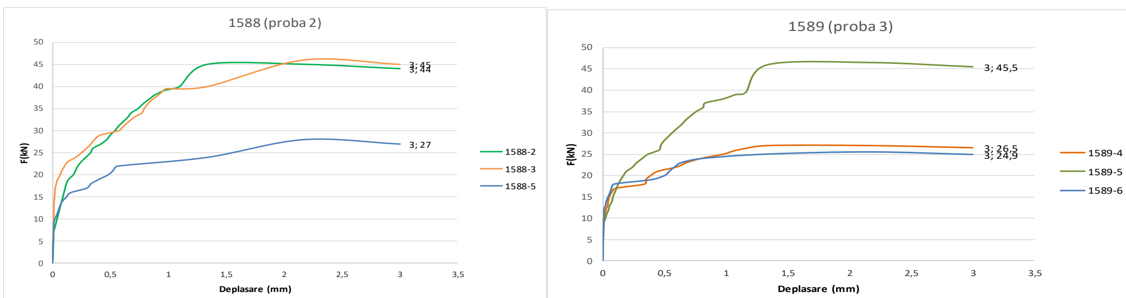

Fig. 2. Experimental Force/CMOD curves obtained from the 3-point bending test.

Experimental results for C $f_{ct\,L}^{f}$ and residual resistances $f_{R,j}$ are presented in Tab.1

Table 1 Experimental results..

Residual strength	specimen						Mean (x_m)	coefficient of variation
	1	2	3	4	5	6		
$f_{ct\,L}^{f}$	4.48	6.72	4.48	4.48	4.48	5.6	5.040	18.59%
$f_{R,1}$	8.96	9.6	6.72	6.72	8.64	6.4	7.840	17.65%
$f_{R,2}$	14.4	12.8	7.68	8.64	14.72	8	11.040	29.83%
$f_{R,3}$	14.4	14.72	8.96	8.64	14.88	8.18	11.630	28.71%
$f_{R,4}$	14.08	14.4	8.64	8.48	14.56	7.97	11.355	28.96%

Based on these results, to determine the characteristic values X_k of the resistors, the following relationship is used.

$$X_k = X_m \cdot (1 - K_m \cdot V_X) \qquad (4.1)$$

where X_k is the characteristic value of the resistance, X_m is the average value, K_m is a parameter that depends on the number of experimental samples and the level of prior knowledge of the coefficient of variation, V_X is the coefficient of variation of the experimental results. value of the parameter K_m for 6 experimental samples and a zero knowledge level is 2,18.

This is how prestressed reinforced concrete purlins were tested:

1. a purlin with transverse reinforcement with stirrups in the central area denoted Gff (Fig.3)

2. two purlins with dispersed steel-fibre reinforcement denoted G1f and G2f (Fig. 4). An overview of the purlins is shown in Fig. 5.

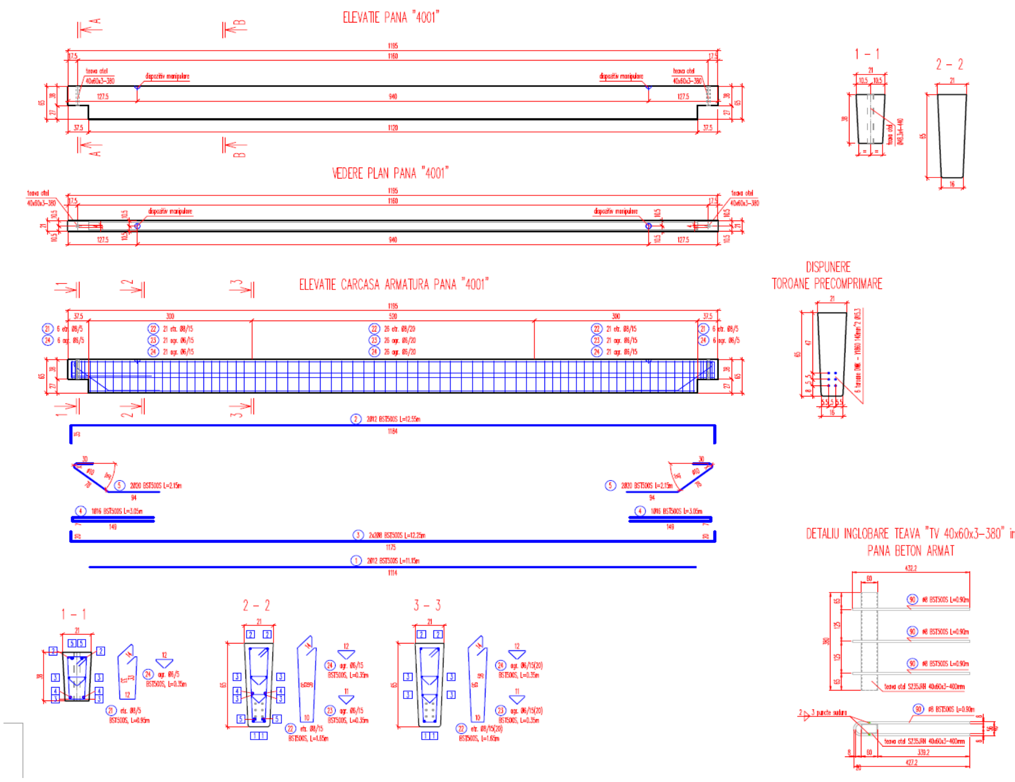

Fig 3. purlin with transverse reinforcement in the form of stirrups in the central area before testing.

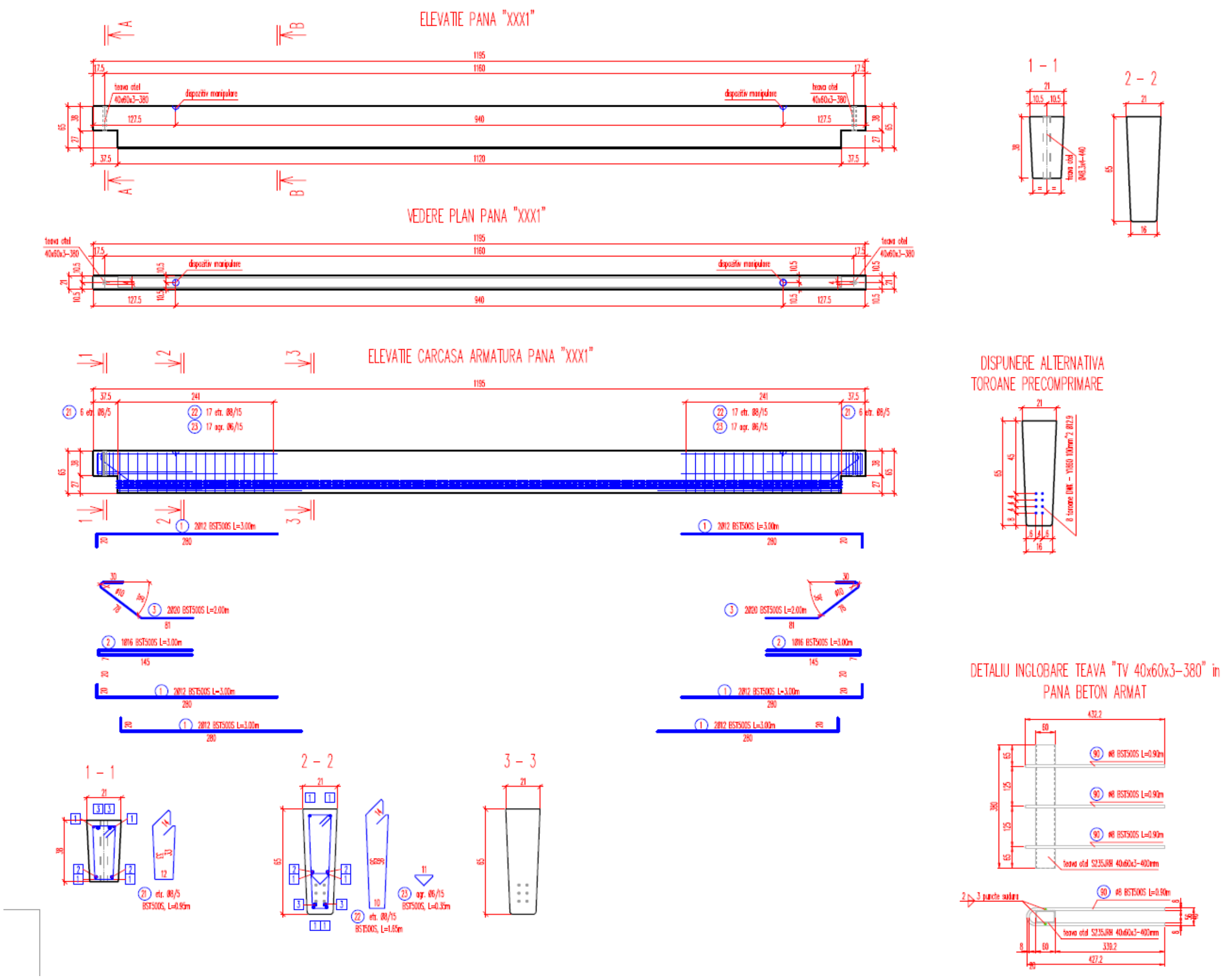

Fig.4. fiber-reinforced purlins before testing (G1f and G2f).

Fig.5. Overview of the purlins.

The loading was performed in stages, with the measurement of deflections, specific deformations in the compressed (upper) and stretched (lower) areas in the central area of the purlin opening and towards the supports, with the recording of the force value at which failure occurred as well as the failure mode.

10.3 Prestressed purlin tests

Three prestressed concrete purlins were tested: one reference purlin, Gff, with conventional transverse stirrups in the central region, and two purlins, G1f and G2f, in which dispersed steel-fibre reinforcement was used in the investigated region. The specimens had comparable geometry, prestressing level and concrete characteristics.

Loading was applied in increments. Deflections and concrete strains were measured in the compressed upper and tensioned lower zones, both in the central span region and toward the supports. The load at failure and the failure mode were recorded.

10.4 Measured quantities

a) The values recorded and analyzed based on the data measured during the test were the following:

1) the specific deformations of the concrete in the upper compressed and lower tensioned areas determined based on the specific deformations at the measurement level;
2) purlin deflection at midspan (f), plotted as a function of load;

b) Recording the values at which the purlins failed and the mode of failure

10.5 Results

The results of specific deformations and deflections were obtained (specific deformation values depending on the applied forces)

1. Classic purlin Gff
2. purlin 1 fiber concrete G1f
3. purlin 2 fiber concrete G2f.

It is mentioned that the deformation values were measured only up to the service load value. As expected, the largest deformations were recorded in the areas in the central part of the purlin opening. In all areas, it was observed that the deformations of the Gff purlin with transverse reinforcement along the entire length were smaller than those corresponding to the G1f purlin. This can be explained by the fact that both the deformations and the deflections are dependent on the bending rigidity, the cracking of the tensioned concrete, the level and efficiency of the prestressing and the behavior under shear force (M-V interaction). Of course, some of these parameters are theoretically the same (prestressing) and also up to the level of the force corresponding to the service, the concrete did not crack. On the other hand, the stirrups indirectly influence all these parameters and the fibers only partially. On the other hand, fibers do not influence/increase the modulus of deformation of concrete, which is an essential factor of rigidity and influences the level of deformations..

Regarding the measured deformation values up to the operating value of the loads, the same observations can be made as those formulated previously, i.e. the lowest deformation values were obtained in the case of the Gff purlin. At values of forces corresponding to the design load, in some cases lower deformations were recorded in the case of the G1f and G2f purlins where FRC was used. This highlights the advantage of the fibers in the behavior after cracking.

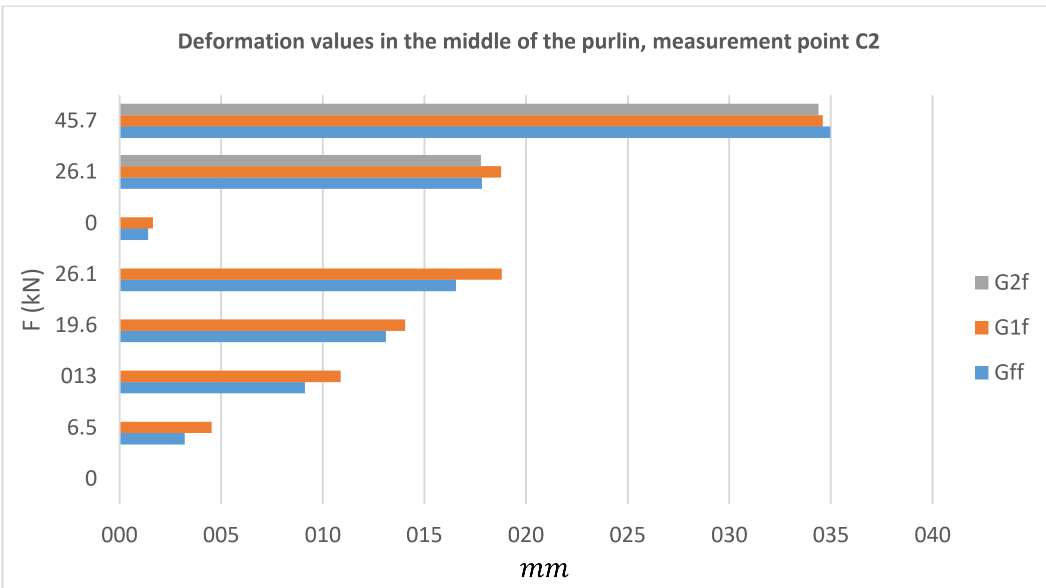

Fig. 6

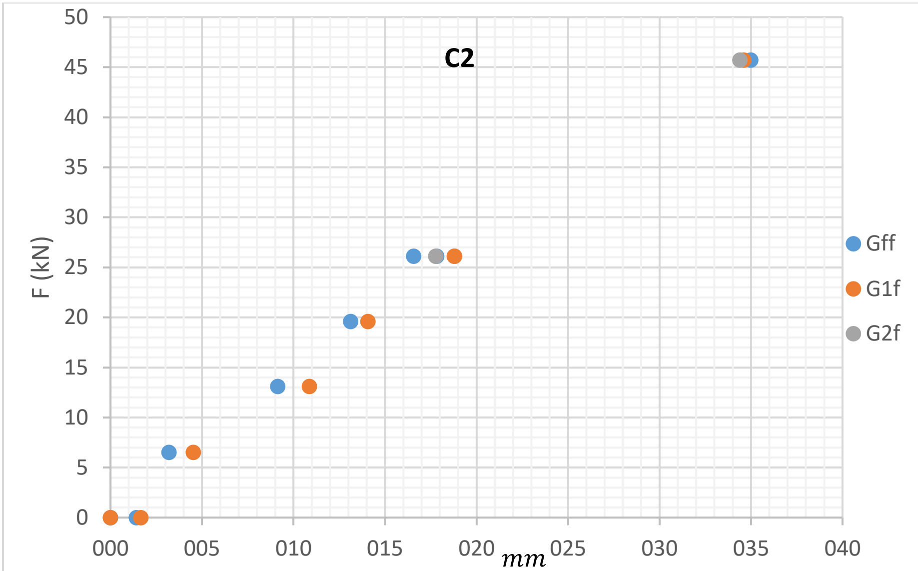

Fig. 7

Figures 6 and 7 show the deflection values for the three purlins. The same observation can be made regarding the fact that the lowest deflection values were recorded up to the service load level for the Gff purlin.

At higher load values, dispersed reinforcement is an advantage.

The experimental results indicate that the prestressed purlin fully reinforced with stirrups exhibits, at service load levels, lower compression and tension fiber deformations and deflections compared to the purlin in which the transverse reinforcement was partially replaced by dispersed reinforcement. This behavior is explained by the higher effective rigidity of the purlin with stirrups, which ensures a superior control of diagonal cracking and a more efficient redistribution of internal stresses. Dispersed reinforcement improves the post-cracking behavior and leads to a limited increase in rigidity and, implicitly, determines a slight reduction in global deformations.

It can be concluded that the prestressed purlin fully reinforced with stirrups presented, in the service load range, lower values of deformations in the compressed and tension fibers, as well as smaller deflections compared to the purlin in which the transverse reinforcement in the central area was replaced by dispersed reinforcement. This behavior indicates a higher effective rigidity of the purlin with classical transverse reinforcement. Dispersed reinforcement did not lead to a significant reduction in the overall deformations of the purlin, confirming that the fibers do not significantly influence the elastic modulus of the concrete and the initial rigidity of the element. The beneficial effect of the fibers is predominantly manifested in the post-cracking range, by controlling the crack opening and increasing the ductility.

According to EN 1992-1-1, deflections are controlled by the effective rigidity Eceff I, the cracking state, the prestressing level. The effective rigidity is evaluated as a combination of the uncracked state (solid concrete), the cracked state (reduced section).

EC2 does not introduce an explicit rigidity increase term for prestressed, fibre-reinforced concrete. So, from the point of view of normative requirements:

- the purlin with stirrups has a better defined and higher rigidity,
- purlins with fibers do not benefit from a "normative" reduction of deflections.

In conclusion:

- Fibers do not increase the modulus of elasticity of concrete, they do not prevent cracking, but make it more "controlled";
- Stirrups: limit the opening of diagonal cracks, stabilize the stress transfer mechanism, increase the overall rigidity of the purlin.

CHAPTER 11. GENERAL CONCLUSIONS AND CONTRIBUTIONS

11.1 General conclusions

This PhD thesis addressed the use of dispersed metal fiber reinforced concrete in prestressed concrete elements subjected to shear force, through an integrated analysis that included theoretical, normative, experimental, technological and parametric studies.

Based on all the investigations carried out, the following general conclusions can be formulated:

1. The critical analysis of the specialized literature highlighted that the use of dispersed metal fiber reinforced concrete is well documented for classical reinforced concrete, but there are few studies on its application in prestressed concrete elements, especially for elements predominantly subjected to shear force.

2. The comparative study of current normative provisions (Eurocode 2, fib Model Code) showed that the design rules for FRC are not explicitly adapted to prestressed concrete elements, and the existing calculation models present a high degree of conservatism or uncertainty in this area..

3. The analysis of technological aspects showed that, for example, fiber distribution and workability significantly influence the structural behavior and variability of experimental results.

4. The studies and parametric calculations carried out have highlighted the determining role of:

- the geometry of the element;
- the characteristics of the concrete and fibers;

on the shear force capacity and on the cracking mechanisms.

5. The experimental program carried out on prestressed concrete purlins with identical geometry, prestress level and concrete characteristics allowed a direct and objective comparison of transverse reinforcement solutions.

6. Experimental results showed that the wedge provided with classical transverse reinforcement in the form of stirrups presented a superior shear force bearing capacity and stiffness compared to purlins with dispersed metal fiber reinforcement, both up to the service load level and at failure.

7. Up to the service load level, the elements with stirrups recorded lower specific deformations and deflections, indicating more efficient cracking control and a stiffer structural behavior compared to the solution with dispersed reinforcement.

8. The purlins dispersedly reinforced with metal fibers failed at lower values of shear force, which indicates that, in the analyzed configuration, dispersed reinforcement cannot fully substitute, in certain cases, the classic transverse reinforcement in prestressed concrete elements predominantly subjected to shear force.

9. However, the analysis of the cracking process and failure mechanisms highlighted the fact that dispersed reinforcement contributes to a more gradual evolution of structural degradation, offering a potential for improving the ductility of the elements.

10. The analysis of technological aspects showed that, for example, fiber distribution and workability significantly influence the structural behavior and variability of experimental results..

11. The correlation of theoretical results, normative, experimental and parametric rules allowed the clarification of the applicability domains of FRC in prestressed concrete elements, as well as the identification of the current limits of this constructive solution.

Overall, the thesis demonstrates that the use of dispersed metal fiber reinforced concrete in prestressed concrete elements subjected to shear force has real potential for improving ductile behavior and cracking control, but, in the analyzed configuration, it cannot fully replace classical transverse reinforcement, requiring hybrid solutions and adapted design rules.

11.2 Personal contributions

11.2.1 Contributions to the state of the art

1. A critical and systematic analysis of the application areas of dispersed metal fiber reinforced concrete was carried out,
2. The results of the main experimental research existing in the specialized literature were synthesized and compared,
3. An analysis of the regulatory provisions was carried out.

11.2.2 Original experimental contributions

4. An original experimental program was designed and carried out on the shear force behavior of prestressed concrete wedges with different transverse reinforcement solutions, under controlled laboratory conditions.
5. Direct experimental tests were carried out on prestressed concrete purlins:
    - with classic transverse reinforcement with stirrups;
    - with dispersed metal fiber reinforcement,

keeping the geometry, prestressing level and concrete characteristics constant.

6. Detailed monitoring of structural behavior was carried out, including:
    - measurement of specific deformations;
    - determining the deflection;
    - identification of failure mechanisms.
7. Based on the experimental results, the difference in structural behavior between purlins with classical transverse reinforcement and those with dispersed reinforcement was highlighted, including the current limits of the partial replacement of stirrups with metal fibers.

11.2.3 Contributions regarding design rules

8. A detailed analysis of the existing design rules for FRC was carried out, with a focus on:
    - shear force capacity assessment;
    - cracking check;
    - scope of applicability of normative relations.

11.2.4 Contributions on technological aspects

9. Technological aspects specific to FRC, relevant for the production of prestressed concrete elements, were analyzed, including:
    - homogeneity of fiber distribution;
    - the influence of fibers on the workability of concrete;
10. The impact of technological aspects on the:
    - cracking behavior;
    - variability of experimental results;
    - overall structural safety.

11.2.5 Contributions through parametric studies and calculations

11. 11. Original studies and parametric calculations were carried out to identify the main factors of influence on:
    - shear force bearing capacity;
    - opening of cracks;
12. Parametric studies have allowed highlighting the influence:
    - the geometric characteristics of the elements;
    - properties of concrete and fibers;

    on the structural behavior of prestressed concrete purlins.

11.2.6 Synthesis contribution

By integrating theoretical, normative, experimental and parametric analyses, the thesis offers a unified and original approach to the use of dispersed metal fiber reinforced concrete in prestressed concrete elements subjected to shear force.

CHAPTER 12. SELECTED BIBLIOGRAPHY

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